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Sensitivity of grass- and alfalfa-reference evapotranspiration to weather station sensor accuracy

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SENSITIVITY OF GRASS- AND ALFALFA-REFERENCE EVAPOTRANSPIRATION TO WEATHER STATION SENSOR ACCURACY

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ABSTRACT. *A sensitivity analysis was conducted to determine the relative effects of measurement errors in climate data input parameters on the accuracy of calculated reference crop evapotranspiration (ET) using the ASCE-EWRI Standardized Reference ET Equation. Data for the period of 1995 to 2008 from an automated weather station located at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas were used for the analysis. Results indicated that grass (ET_{os}) and alfalfa (ET_{rs}) reference crop ET were most sensitive to measurement errors in wind speed and air temperature followed by incoming shortwave (solar) radiation, and that data sensitivity was greater during the mid-summer growing season in this semi-arid region. Given the highly advective conditions of the Texas High Plains and the relative sensitivity of ET calculations to errors in wind speed, special care is recommended in siting, sensor placement, and sensor maintenance for agriculturally-based ET weather stations.*

Keywords. *Sensitivity analysis, Weather data, Weather stations.*

Evapotranspiration (ET) is a combined term that includes evaporation from soil and wet surfaces and transpiration by plants in estimating crop water demand. Although the ET process is also influenced by surface characteristics, including soil water status, ET is driven primarily by meteorological conditions, including air temperature, relative humidity (vapor pressure deficit), incoming shortwave radiation, and wind speed. These data are acquired through use of specially equipped meteorological “weather” stations, strategically located and grouped into ET networks. Data from these stations are applied to an ET model (equation) to calculate reference crop (well-watered grass or alfalfa) ET. Crop-specific coefficient curves are used to derive crop ET (ET_c) from standardized reference crop ET (ET_{os} or ET_{rs}); for a given crop at a given growth stage, crop ET is calculated by multiplying the reference crop ET by the appropriate crop coefficient. Seasonal variations in crop coefficients due to crop-specific and growth stage specific water demand are reflected in the coefficient curve; crop water demand generally is very low during crop establishment, increasing through vegetative development, reaching a maximum at full canopy or fruit initiation, and often tapering off as the crop reaches maturity. Accuracy of the ET estimates depends upon the correctness of the model, as well as the accuracy of the data used in the calculation(s). This accuracy, in turn, depends upon the accuracy and correct calibration of sensors and representative siting of the weather stations.

High levels of accuracy and quality of data are desired and expected from ET networks. Realistically, however, some data inaccuracy due to weather station placement, sensor calibration drift, and other factors is inevitable due to the difficulties in operating these stations under challenging remote environments (Marek et al., 2010). Meteorological data acquisition and quality assurance/quality control, instrumentation maintenance, technical support, and related network maintenance operations are underlying necessities that must be implemented and sustained for the data to be accurate and representative of field conditions. Standards and

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recommendations regarding data requirements, site and sensor maintenance, measurements and reporting practices for agricultural weather stations are addressed in *ASABE Standards* (2006), Allen et al. (2005), and other sources. Data quality assurance/quality control methods include laboratory and field sensor calibration, as well as automated and manual data checks (Palmer and Hamel, 2009) and statistical quality control limits (Eching and Snyder, 2004) methods intended to help identify data errors for subsequent weather sensor trouble-shooting.

Because agricultural weather stations are electronic and generally installed in remote locations, data can be subject to measurement biases caused by sensor malfunction, aging, miscalibration, alignment problems, contamination, and siting, as well as data logger programming problems (Allen, 2008). Allen (1996) presented guidelines for assessing weather station data integrity and reasonableness, environmental effects on data parameters and approaches to adjust data to account for environmental effects.

When applying the combination-based energy balance ET equations, it is desirable to measure the required microclimatic data over a reference surface (preferably a well maintained grass) rather than above non-reference surfaces. However, because of difficulties of establishing and maintaining a reference surface for long periods of time, other researchers have investigated the impact of climate data measured over non-reference surfaces on the accuracy of reference evapotranspiration calculations. For example, Irmak and Odhiambo (2009) observed that microclimate data measured above non-stressed maize and grass canopies in sub-humid Nebraska produced similar results in Penman-Monteith reference ET calculations. The main differences in microclimate data between the two surfaces were wind speed and aerodynamic resistance; wind speed at 2-m height was 15% to 20% higher over the grass canopy than over the maize canopy during the 2-year study period, but did not result in significantly different grass (ET_{os}) and alfalfa (ET_{rs}) reference ET calculations. Skaggs and Irmak (2012) evaluated the impact of climate data measured over non-stressed soybean and grass canopies on reference ET calculations in 2007 and 2008 growing seasons. They analyzed the measured and estimated microclimate variables, including net radiation (R_n), average air temperature (T_{ave}), dew point temperature (T_d), average relative humidity (RH_{ave}), aerodynamic resistance (r_a), and wind speed at 3 m (u_3) of a soybean and a grass canopy in south-central Nebraska. According to Skaggs and Irmak (2012), differences in r_a of the two crops and u_3 of the two fields were most significant. The average percent differences in u_3 between the soybean and grass fields were 9.0% and 9.8% for 2007 and 2008, respectively. Although average percent differences in T_{ave}, RH_{ave}, and T_d were not that large, there were distinct seasonalities to the differences. The ET_{os} and ET_{rs} calculations using data from the soybean ($ET_{os\text{-}s}$ and $ET_{rs\text{-}s}$) and grass ($ET_{os\text{-}g}$ and $ET_{rs\text{-}g}$) canopies were compared daily and seasonally. Seasonal total ET_{os} and ET_{rs} estimates using soybean and grass microclimate data were very close and were within 1% and 2% during 2007 ($ET_{os\text{-}g}$ = 583 mm and $ET_{os\text{-}s}$ = 576 mm; $ET_{rs\text{-}g}$ = 751 mm and $ET_{rs\text{-}s}$ = 733 mm) and 4% and 5% during 2008 ($ET_{os\text{-}g}$ = 554 mm and $ET_{os\text{-}s}$ = 531 mm; $ET_{rs\text{-}g}$ = 707 mm and $ET_{rs\text{-}s}$ = 669 mm). In 2007, differences in temperature variables were most correlated to differences in ET_{ref} estimates. In 2008, differences in ET_{os} and ET_{rs} were most correlated with differences in T_{ave}, RH_{ave}, and u_3.

The relative error in ET estimates resulting from inaccurate data have been addressed through statistical approaches. Droogers and Allen (2002) assumed errors up to two standard deviations to compare Penman-Monteith and Hargreaves methods to calculate reference ET with inaccurate weather data. This method assumes errors in meteorological observations to be random errors rather than systematic as would be expected with most sensor errors. Sithole et al. (2010) independently adjusted data parameters using 50%, 75%, 125%, and 150% of long-term mean values, applying absolute changes in Penman-Monteith calculated ET from the long-term mean baseline to determine relative effects of solar radiation, temperature, relative humidity, and wind speed, attributing a percentage contribution of each parameter to the overall evapotranspiration estimate for sugarcane in South Africa.

Irmak et al. (2006) analyzed relative errors in reference crop water use calculated using the ASCE Standardized Penman-Monteith equation by making small incremental changes in weather data used for different climates in sub-humid Nebraska. Crop water use was most sensitive to relative humidity (expressed in vapor pressure deficit). Sensitivity to other parameters (wind speed, solar radiation) varied with climate type and season (summer vs. winter). Bakhtiari and Liaghat (2011) conducted a similar study referencing their methodology in the arid to semi-arid Kerman Province in Iran. The ASCE-Penman-Monteith grass reference evapotransiration was found to be sensitive to vapor pressure deficit in all months; to wind speed during the March to November period; and more sensitive to solar radiation during the summer than in the winter.

Gong et al., (2006) found that in the Yangtze River basin (China), evapotranspiration calculated by the FAO-56 Penman-Monteith Equation (Allen et al., 1998) was most sensitive to relative humidity, followed by shortwave radiation, air temperature, and wind speed. They also noted that sensitivity varied by region and that relative sensitivity (indicated by sensitivity coefficient) varied seasonally. Liqiao et al. (2008) also noted relatively high sensitivity to relative humidity and seasonal and spatial variances in sensitivity of reference ET calculated by the FAO-56 Penman-Monteith Equation for the Tao'er River Basin of the northeastern China. Conversely, Ambas and Baltas (2011) reported that based on standard-deviation-based sensitivity analyses of multiple evapotranspiration models applied to meteorological data from Florina, Western Macedonia (Greece), solar radiation was the most important (parameter of greatest sensitivity coefficient), followed by temperature, and that wind speed and relative humidity "are not important climatic parameters for the calculation of evapotranspiration." Others noting seasonal and spatial (geographic) variation in sensitivity to climate data of calculated evapotranspiration include Estevez et al. (2009) and Moratiel et al. (2010).

Sensitivity of each weather parameter and consequent magnitude of errors may vary from one geographic region to another, and it can be significant if the regions are located in different climatic zones (e.g. semi-arid vs. sub-humid). Therefore, the objective of this study was to determine the relative effects of measurement errors in climate data input parameters on the accuracy of calculated reference crop ET using the ASCE-EWRI Standardized Reference ET Equation in the semi-arid Texas High Plains. This study was conducted as part of a statewide assessment of ET weather station networks project (Marek et al., 2010). The sensitivity analysis of weather data from one location was conducted to determine effects of sensor-related data measurement inaccuracies on calculated reference ET (ET_{ref} as ET_{os} and $ET_{rs,}$), where the subscript “os” relates to a short or grass reference surface and “rs” relates to a tall or alfalfa reference surface.

MATERIALS AND METHODS

Climate data for the period of 1995 to 2008 from a weather station located at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas (fig. 1) were used in this analysis. The weather station site has a well-maintained, irrigated grass cover with sufficient fetch between the weather station and surrounding agricultural fields representative of commercial agricultural conditions.

ET_{ref} values were calculated using the ASCE Standardized Reference ET Equation for both ET_{os} and ET_{rs} (Allen et al., 2005). The ET_{ref} values were calculated for hourly intervals and summed for a 24-h period to provide a daily value. Once the base ET_{ref} values were known, one climate parameter at a time was modified while keeping all other parameters constant to determine the effect of that parameter on the ET_{ref} values. This was done individually for four climate parameters: air temperature, wind speed, solar radiation, and dew point temperature. Incremental changes were reflective of the range of errors observed in weather data among various weather station networks in the region in a comprehensive statewide assessment of ET networks (Marek et al., 2010). The hourly air temperature and dew point temperatures were changed by 2°C intervals from -6°C to +6°C. These new values were then used to calculate ET_{os} and ET_{rs}. Similarly, hourly wind speed was changed at 2 m/s intervals from -6 to +6 m/s, with an additional constraint that wind speed would not drop below 0 m/s. Hourly solar radiation was altered ±25, 50, and 75 W m^{-2} (out of a typical maximum value of approximately 1050 W m^{-2}, which is often observed in the Texas High Plains in summer months during clear sky conditions). For reference, mean monthly values of air temperature (°C), wind speed (m/s), dew point temperature (°C), and solar radiation (W m^{-2}) for the dataset are summarized in figure 2.

Once this was completed for each parameter individually, the impact of two parameters adjusted simultaneously on ET_{ref} was evaluated. In the paired parameter analysis, hourly wind speed was elevated by 2 m/s and the hourly air temperature was altered at 2°C intervals from -6 to +6°C. This procedure was repeated with the wind speed reduced by 2 m/s, thus elucidating the combined effects on ET_{ref} calculations of inaccuracies of two data parameters.

To quantify sensitivity of calculated ET_{ref} to each climate parameter, a sensitivity coefficient (C_s) was calculated ($C_s = CH_{ETref}/CH_{CV}$; where $CH_{ETref}$was the change in ET_{ref} with respect to climate variable, and CH_{CV} was the change in climate variable) (Irmak et al., 2006). The C_s for each climate variable was calculated by dividing the value of change in ET_{os} or ET_{rs} by amount of increase or decrease in the value of climate input parameter (25 W m^{-2} increase or decrease is considered equivalent to one unit for solar radiation, and one unit increase or decrease was used for all other variables) in each climate parameter on a daily basis. Finally, sensitivity coefficients for all climate parameters were compared to determine sensitivity of ET to each parameter over different cropping seasons. The higher the C_s value for a climate parameter, the more sensitive the ET calculation is to variation in that parameter.

(a)

(b)

Figure 1. (a) Location of the USDA-ARS Conservation and Production Laboratory at Bushland, Texas; and (b) photograph of the weather station site.

RESULTS AND DISCUSSION

Daily ET_{os} and ET_{rs} were calculated using measured values from the Bushland weather station dataset; they were also calculated using the dataset with adjusted parameter values as described above. Resulting calculated ET_{os} and ET_{rs} are presented in figures 3-8, showing the effects of data changes that would represent errors in measurements, as would be anticipated from sensor and siting based problems.

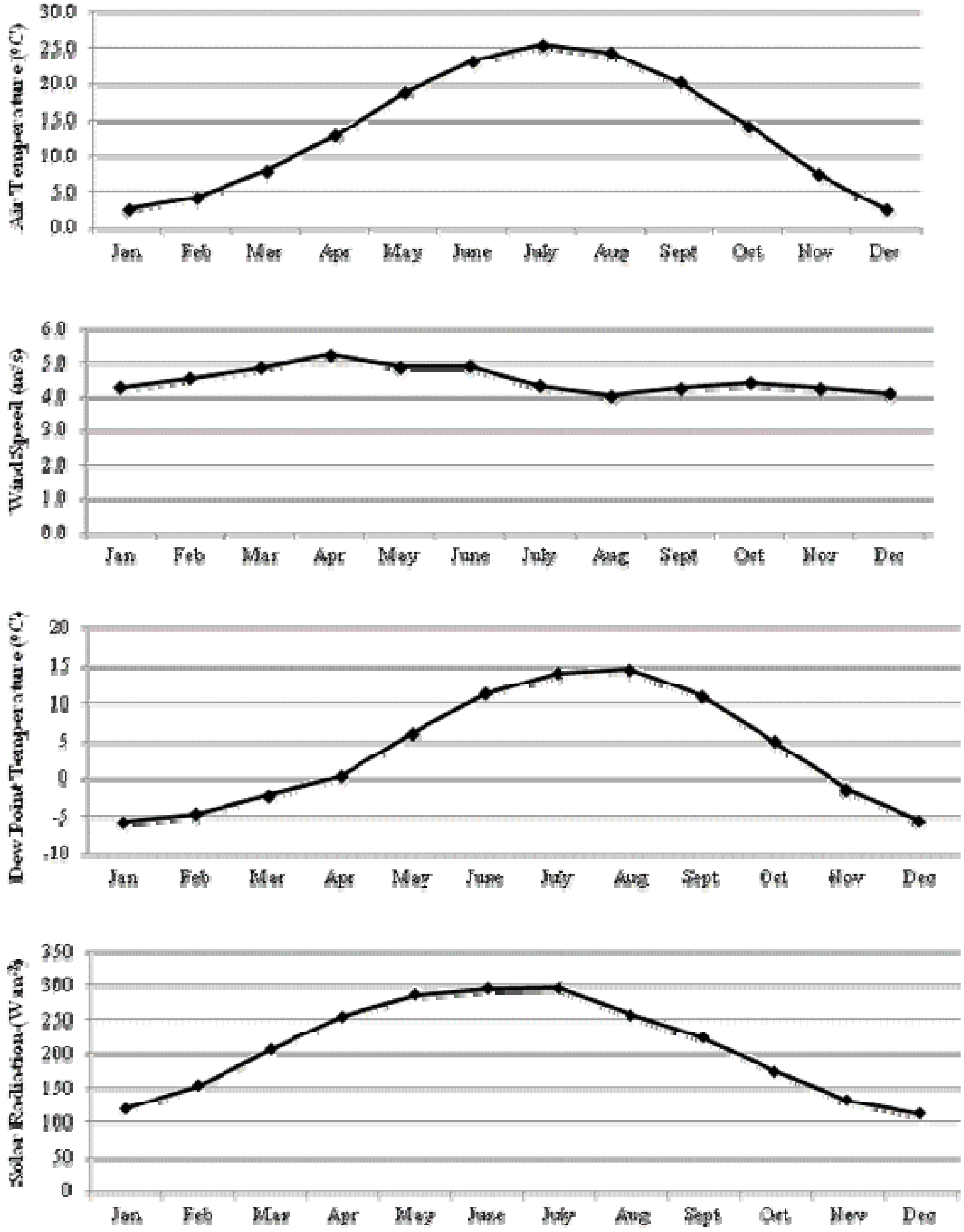

Figure 2. Mean monthly values of air temperature (°C), wind speed (m/s), dew point temperature (°C), and solar radiation (W m^{-2}) for the period 1995-2008 at Bushland, Texas.

Figure 3 illustrates ET_{os} and ET_{rs} responses to changes in air temperature individually while values of all other climate parameters were held constant. A 2°C increase in air temperature increased the ET_{os} and ET_{rs} by 0.5 and 0.75 mm, respectively. The relationship seems almost linear with increasing temperatures, especially for ET_{os}, however non-linearity is more obvious with air temperature decreases (fig. 1). Similar trends were found with -2°C,-4°C,-6°C, +4°C, and +6°C variants. Increases in air temperature by 2°C, 4°C, and 6°C resulted in increases of 0.5, 1.0, and 1.5 mm/d in ET_{os} and 0.75, 1.6, and 2.4 mm/d in ET_{rs}, respectively. Decreases in air temperature by 2°C, 4°C, and 6°C resulted in decreases of 0.5, 0.8, 1.3 mm/d in ET_{os} and 0.75, 1.4, and 2.0 mm/d in ET_{rs}, respectively.

For the wind speed variations (fig. 4), neither the ET_{os} nor ET_{rs} relationship was linear. In fact, changes in wind speed resulted in approximately twice the change in ET_{rs} compared to ET_{os}. Wind speed changes of -6, -4, -2, +2, +4, and +6 m/s resulted in approximately -1.2, -0.9, -0.5, +0.4, +0.75, and +1.0 mm/d change in ET_{os} and -2.4, -1.9, -1, +0.8, +1.5, and +2.0 mm/d change in ET_{rs}, respectively.

Figure 5 illustrates the effects of changes in hourly dew point temperature on daily ET_{os} and ET_{rs}. The inverse relationship between dew point temperature and reference ET is expected, as an increase in dew point temperature indicates higher humidity and therefore lower vapor pressure deficit and ET demand. Dew point temperature changes by -6°C, -4°C, -2°C, +2°C, +4°C, and +6°C resulted in +0.7, +0.5, +0.3, -0.25, -0.5, and -0.7 mm/d

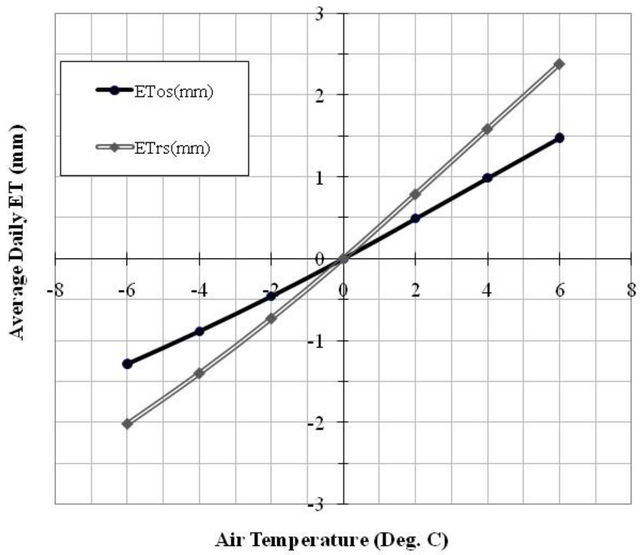

Figure 3. Effects of increasing and decreasing hourly air temperature on daily grass (ET_{os}) and alfalfa (ET_{rs}) reference ET.

change in ET_{os} and +1.2, +0.8, +0.45, -0.45, -0.8, and -1.3 mm/d change in ET_{rs}, respectively.

Figure 6 illustrates the effects of changes in hourly solar radiation on daily ET_{os} and ET_{rs}. Responses of calculated ET_{os} and ET_{rs} to changes in solar radiation were less pronounced than those for air temperature, wind speed, and dew point temperature. Also, differences between responses in ET_{os} and ET_{rs} to solar radiation were smaller. Changes in solar radiation by -75, -50, -25, +25, +50, and +75 W m^{-2} resulted in changes by approximately -0.3, -0.2, -0.1, +0.2, +0.4, and +0.6 mm/d in ET_{os} and approximately -0.3, -0.2, -0.1, +0.25, +0.5, and +0.7 mm/d in ET_{rs}.

Figure 7 illustrates changes in ET_{os} in response to changes in hourly air temperature in combination with changes of -2, 0, and +2 m/s wind speed increments. The figure indicates the nonlinearity of ET_{os} calculation response to changes in air temperature and the nonlinearity

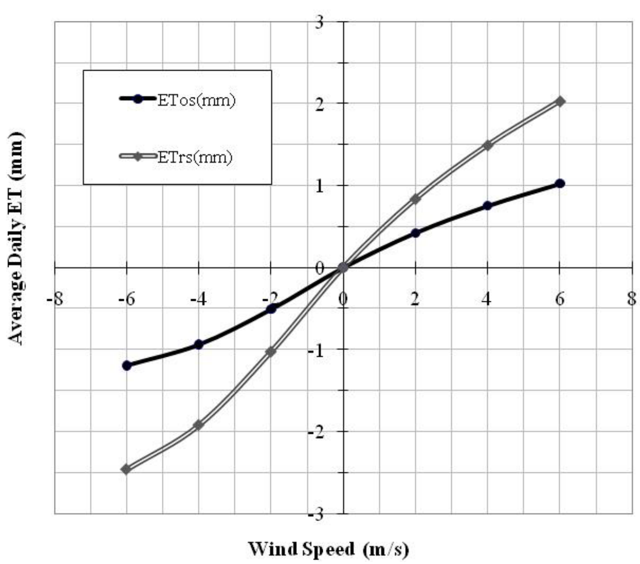

Figure 4. Effects of increasing and decreasing hourly wind speed on daily grass (ET_{os}) and alfalfa (ET_{rs}) reference ET.

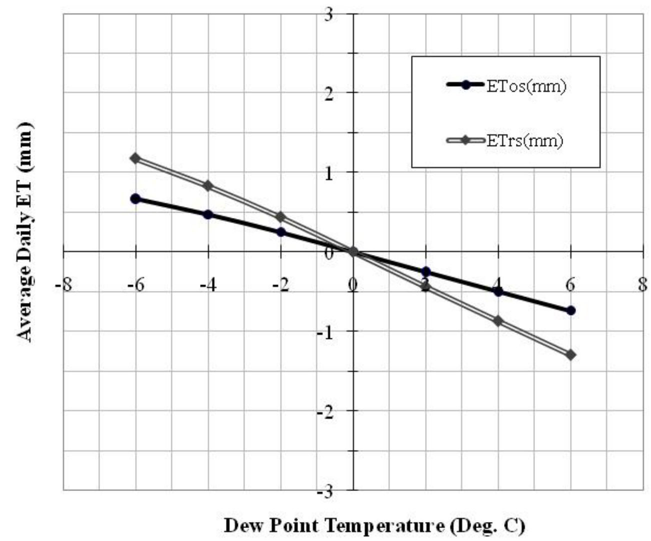

Figure 5. Effects of increasing and decreasing hourly dew point temperature on daily grass (ET_{os}) and alfalfa (ET_{rs}) reference ET.

of the pair-wise response to both air temperature and wind speed. Slopes of the curves were approximately 0.16, 0.23, and 0.30 for the reduced wind speed, base wind speed, and increased wind speed, respectively. The response curves seem to converge at some point beyond base temperature -6°C at a calculated ET_{os} approximately base value -1.5 mm/d.

ET_{rs} responses (fig. 8) to simultaneous variation of wind speed and air temperature were similar to those of ET_{os}, but at a somewhat higher magnitude. Slopes of the curves were approximately 0.24, 0.37, and 0.47 for the reduced wind speed, base wind speed, and increased wind speed responses to changes in air temperature. Similar to the ET_{os} pair-wise analysis, the curves seem to converge at some point beyond base temperature -6°C at a calculated ET_{rs} of approximately base value -2.5 or -3 mm/d.

Figures 9 and 10 illustrate the sensitivities of ET_{os} and ET_{rs} to variations in air temperature, wind speed, dew point temperature, and solar radiation, respectively. Greater

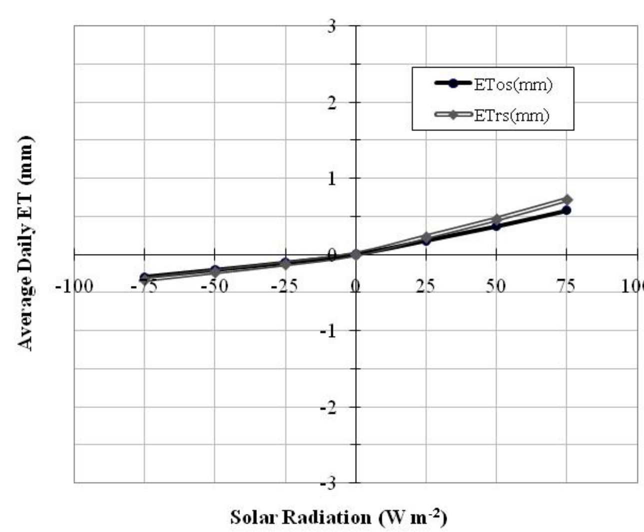

Figure 6. Effects of increasing and decreasing hourly solar radiation on daily grass (ET_{os}) and alfalfa (ET_{rs}) reference ET.

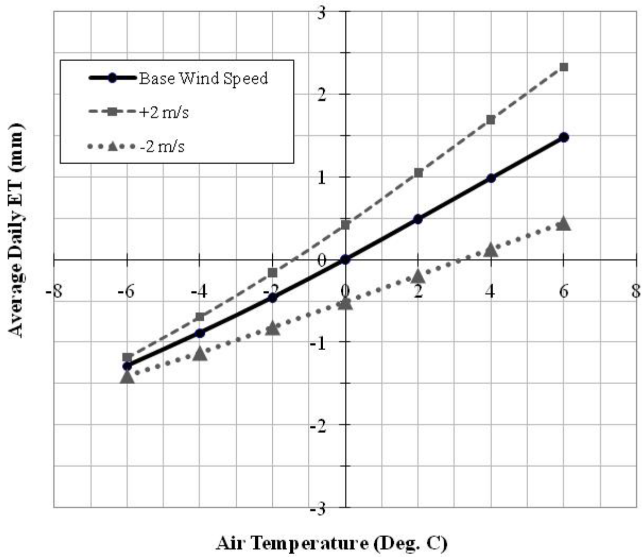

Figure 7. Effects of simultaneous changes in wind speed and air temperature on daily grass reference ET (ET_{os}).

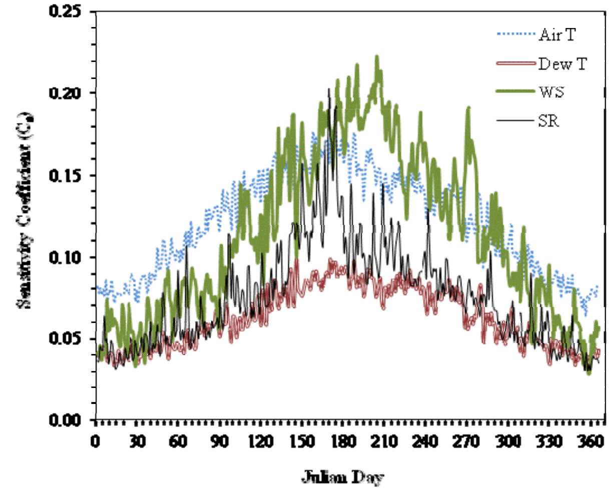

Figure 9. Daily average ET_{os} sensitivity coefficients for air temperature, dew point temperature, wind speed, and solar radiation.

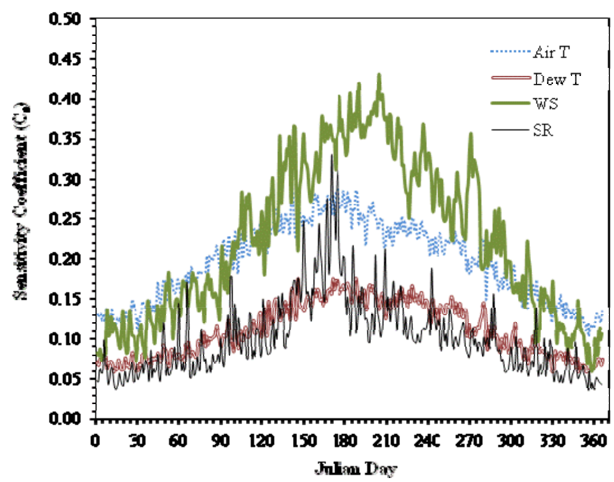

Figure 10. Daily average ET_{rs} sensitivity coefficients for air temperature, dew point temperature, wind speed, and solar radiation.

values of sensitivity coefficients indicate greater impact of errors in data on the calculated ET_{ref} values. Individual parameters significantly affect ET_{os} and ET_{rs} calculations. These sensitivities are greater during the summer period corresponding to the growing season for most crops. Wind speed was found to be the most impacting parameter followed by air temperature. However, solar radiation errors also significantly affect ET calculation, especially during the mid-summer growing period. Dew point temperature generally indicated lower impact, yet also showed seasonal variation with an increased sensitivity coefficient during the mid-summer growing season. Pair-wise sensitivity analysis confirmed that effects of errors in multiple data parameters would compound the resultant errors in ET calculations.

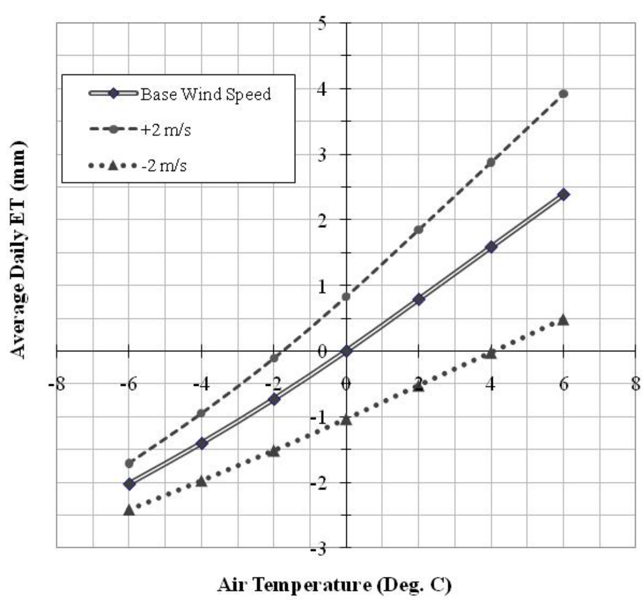

Figure 8. Effects of simultaneous changes in wind speed and air temperature on daily alfalfa reference ET (ET_{rs}).

CONCLUSIONS

A sensitivity analysis was conducted to determine relative effects of errors in climate data input parameters on the accuracy of calculated reference crop evapotranspiration (ET_{ref}) using the ASCE-EWRI Standardized Reference ET Equation. Data for the period of 1995 to 2008 collected with an automated weather station located at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas were used in the analysis. Results indicated that for these climate and geographic conditions, grass (ET_{os}) and alfalfa (ET_{rs}) reference crop ET calculations were most sensitive to errors in wind speed and air temperature, and that sensitivity was greater during the mid-summer growing season. Responses to changes in air temperature, wind speed, and humidity (dew point temperature) were greater for ET_{rs} than for ET_{os}. However, it should be noted that magnitude of the sensitivity of reference crop ET to measurement errors in the weather parameters may vary from location to location due to interactive effects of weather parameters on the calculation of reference crop ET.

Given the highly advective conditions of the Texas High Plains, high temporal and spatial variability in wind speed and direction, high level of wear on bearings in anemometers, and the relative sensitivity of ET calculations to errors in wind speed, special care is warranted in siting, sensor placement, and sensor maintenance for agriculturally-based ET weather stations. Results of this study were incorporated into recommendations regarding degree of sensor accuracy necessary to achieve acceptably accurate ET estimates.

Acknowledgements

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